Concrete Gravity Structures

Best Practices in Dam and Levee Safety Risk Analysis

Part E – Concrete Structures

Chapter E-3

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US Army Corps
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Outline

- Objectives
- Key concepts
- Case histories
- Design vs. risk analysis
- Cracked base analysis
- Event trees (normal, flood, and earthquake loading)
- Earthquake nodal estimates

Objectives

- Understand the mechanisms that affect potential gravity structure failure

- Understand how to construct an event tree to represent potential gravity structure failure

- Understand how to estimate event tree probabilities and probability of gravity structure failure

About this Presentation

- Sometimes potential failure modes for concrete gravity structures are divided into "Internal" and "Global" modes

- Internal modes refer to instability through the concrete itself

- Global modes refer to instability at the foundation contact or within the foundation

- This presentation focuses on Internal and Global "at the foundation contact" potential failure modes, which are often evaluated in a similar manner

- Global instability within the foundation (deep or shallow) is covered in a different presentation

- For gravity dams founded on alluvial foundations – see internal erosion section

Key Concepts

- Gravity structures rely on mass for stability
- Weak lift joints or the rock foundation contact can be potential planes of weakness, joint cleanup and placement are critical
- Foundation rock interface typically rough with high strength due to blasting
- Changes in slope or geometry can be locations of stress concentrations
- Existing crack patterns can affect behavior
- Drains are first line of defense against instability
- Selection of strength parameters and analysis techniques is important
- Limit state is not necessarily failure
- Shear keys or keyed joints aid stability

Keyed Contraction Joints
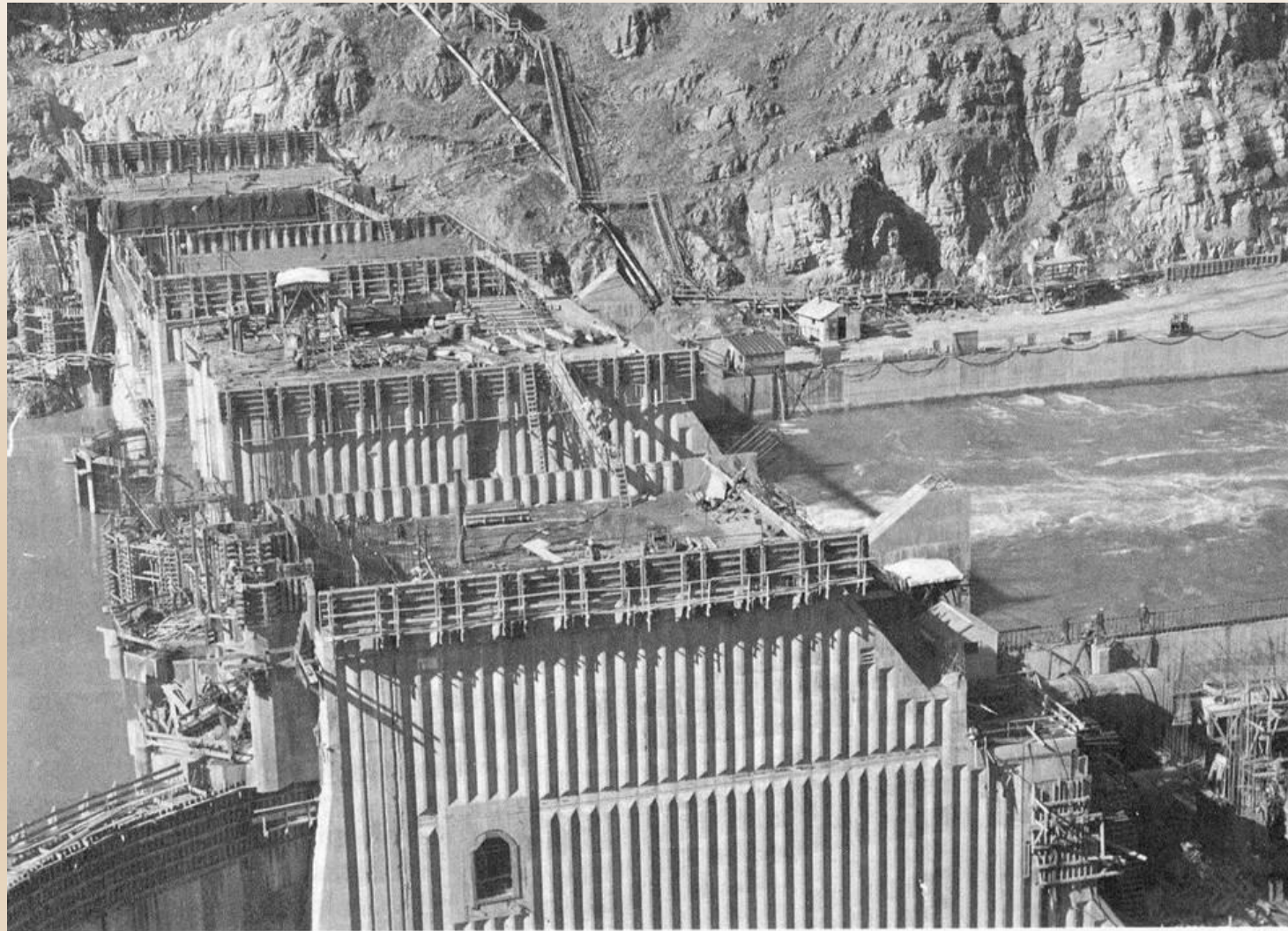
Case Histories

Case History - Bouzey Dam, France

- 72' high masonry gravity dam built in 1884

- Structural damage on initial filling included shearing of key, but no vertical significant vertical displacement when water reached 10-ft from crest

- Other damage during initial filling included cracking along upstream heel of the dam

- D/S lower third of the dam was strengthened by providing a buttress and keying it deeper into the foundation (horizontally-bedded sandstone)

- Subsequent filling in 1895 up to 2-ft from the crest resulted in the upper narrow section of the dam suddenly failing on April 27, 1895

- The failure released a torrent of water on the village of Bouzey causing more than 100 deaths
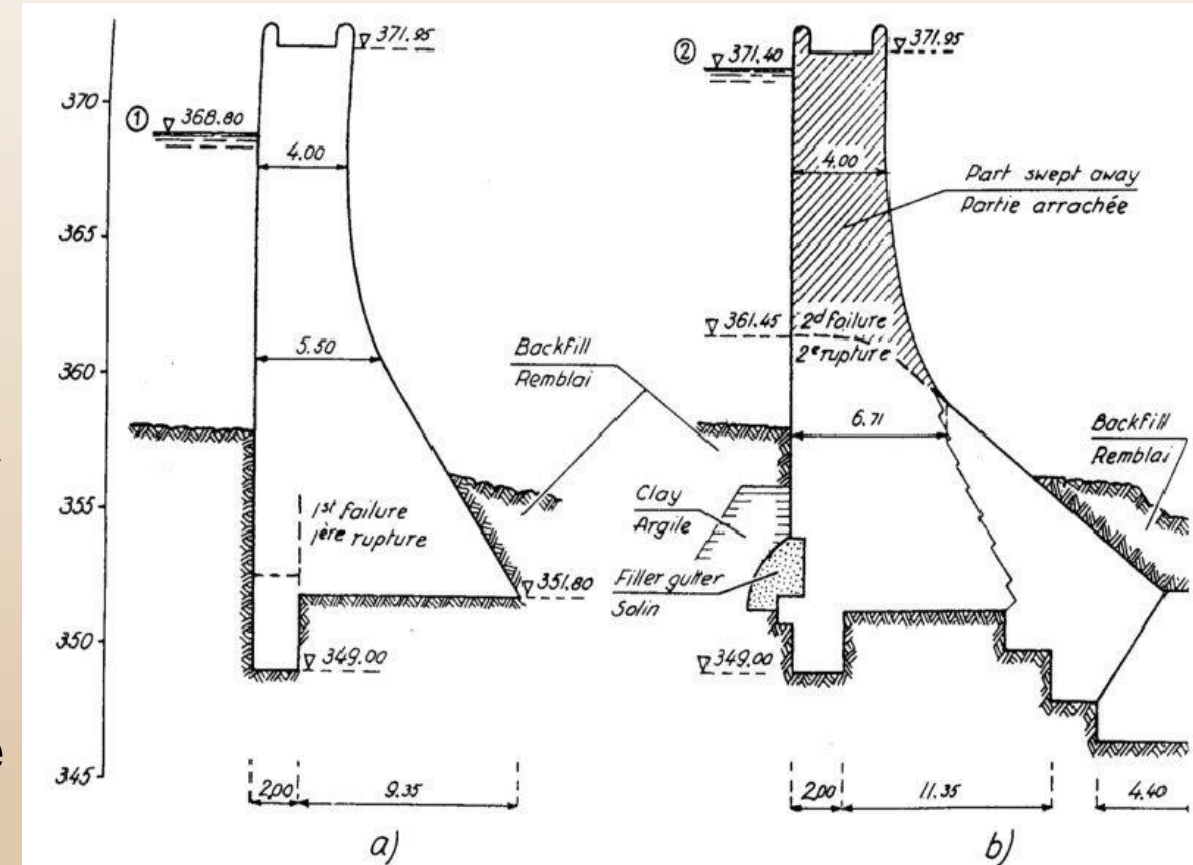

Internal instability failure mode

Bouzey Dam

- Tensile crack likely originated at the upstream face during the first filling due to excessive moment at the base of the narrow upper section

- No structural modifications made to upper section of dam, only buttress section added to base of dam

- Crack propagated through the structure and did not have enough shear strength (friction) to resist the driving forces brought on by the 2nd filling (first time to within 2-ft of crest)

- Masonry mortar used dirty sand of poor quality

- Uplift recognized as a contributor for first time

- Horizontal joint opening and subsequent uplift resulted in failure
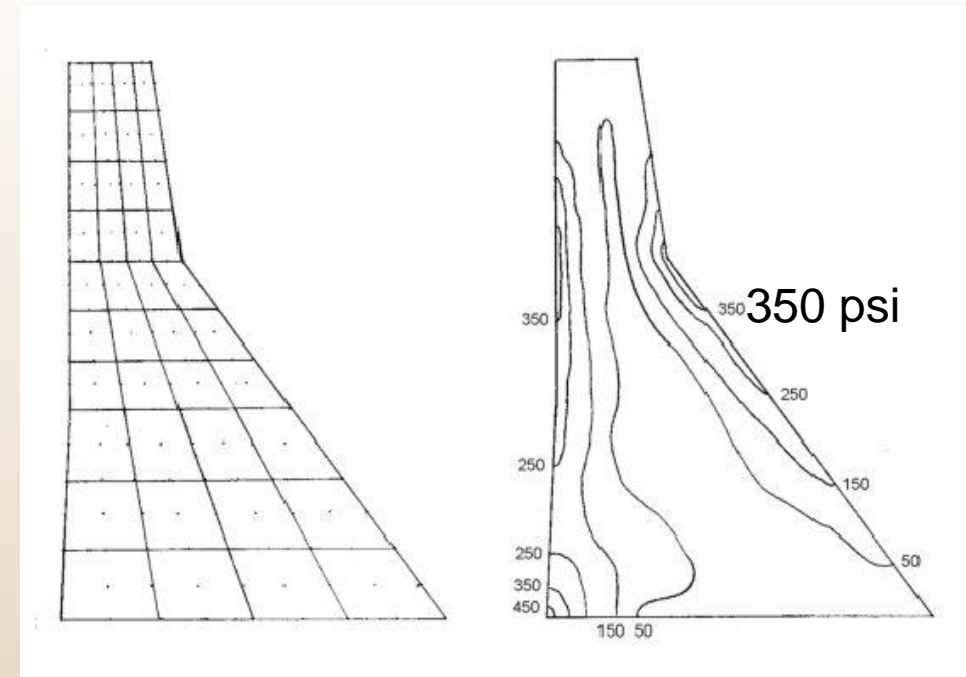
Koyna Dam, India

- Straight axis gravity dam located in SW India

- 340-ft high, 2800-ft long

- 50-ft wide monoliths

- Joints not keyed, but contained copper water seals

- Modifications during construction caused a change in geometry of non-overflow monolith cross section

- Steeper d/s slope near top of monolith

Koyna Dam

350 psi

Results of EAGD analysis
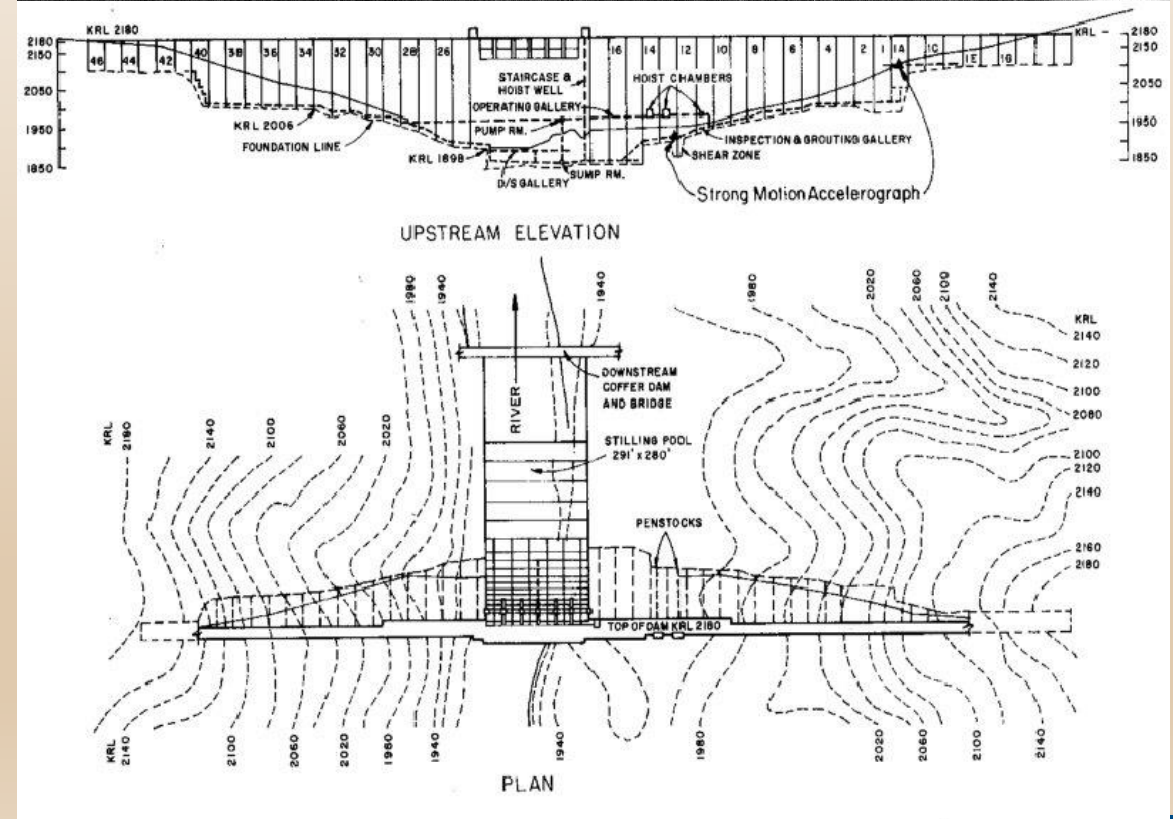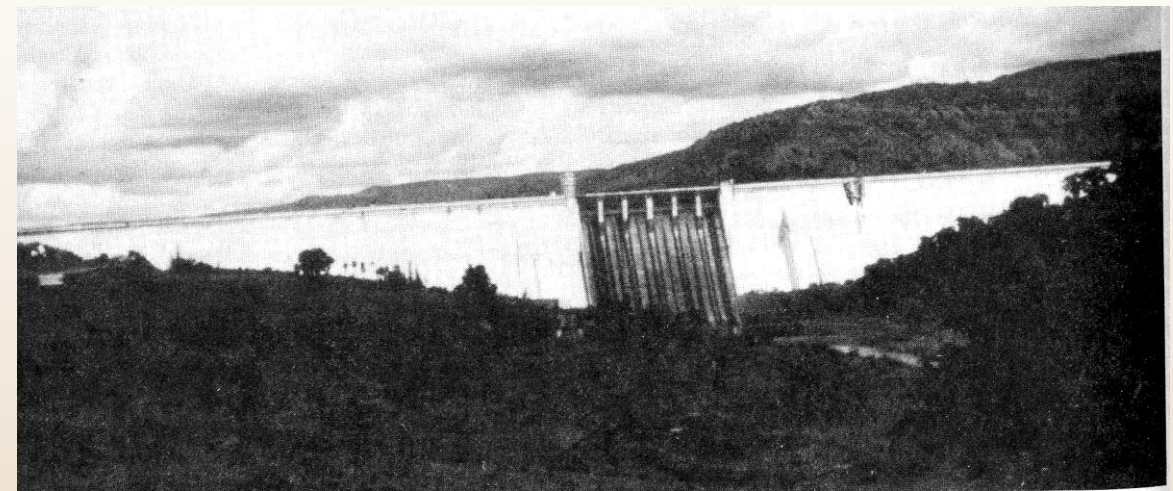
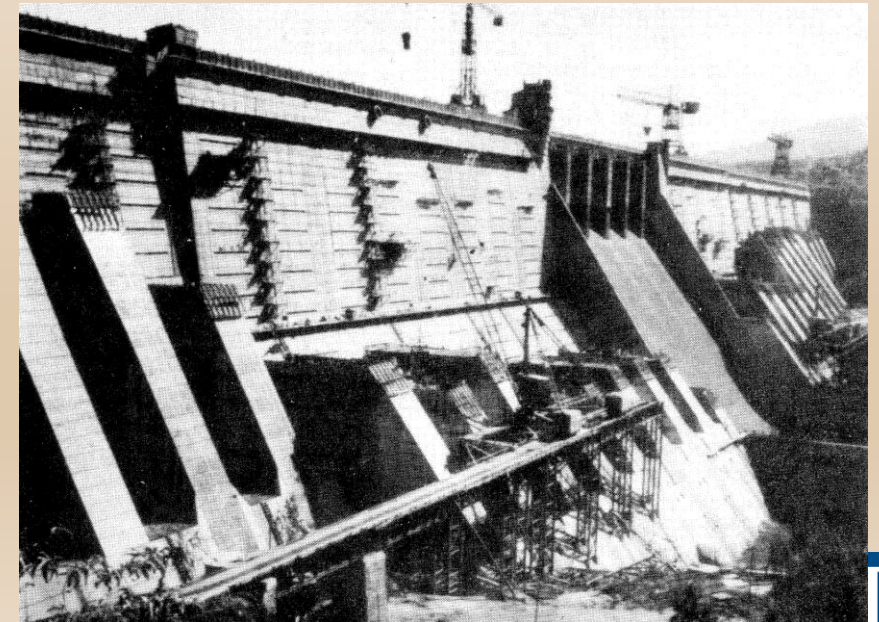- M6.5 EQ on 12/11/76 with epicenter only 13 km from dam
- Reservoir within 40-ft of crest at time of EQ
- Deep horizontal cracks u/s and d/s faces occurred causing significant leakage in most non-overflow monoliths near change in slope
- Modern linear elastic analysis showed tensile stresses > tensile strength
- Dam strengthened with buttresses and anchors

Internal instability failure mode

Post Earthquake Strengthening

Design versus Risk Analysis

| DESIGN CONSIDERATIONS	RISK ANALYSIS CONSIDERATIONS
• Analysis is generally deterministic	• Analysis is probabilistic
• Incorporation of FS for stability analysis	• No safety factors considered
•Design considers O&M needs as well as dam safety	• Account for frequency of loading
• Lower FS for non-routine loads	• Should try to account for side friction when it is likely to provide additional resistance
• Do not account for side friction	
• Typically assume ineffective drains at least as one load case	• Account for actual drain efficiency with data
• Generally assume lower bound values for resisting forces (friction, etc)	• If no data available, use information regarding environment, maintenance, etc. to determine a best estimate
• Generally don't consider interlock resistance for monoliths with keys	• Full range of values for analysis parameter with best estimates, bounds, and distributions
• FS < 1 is 'ultimate' limit state for design	• FS < 1 associated with a traditional stability analysis is not likely the limit state for RA
• Past performance is generally not considered	• Past performance can be a significant contributor to estimating risks
•May consider 3-D effects and risk-based loading	

Cracked Base Analysis

- Most published methodology and criteria are geared more towards design and are generally too conservative for risk analysis purposes
  - Full uplift at crack tip for most concrete dams is not reasonable due to the fact that the foundation permeability > permeability of the crack
  - Drains remain partially effective even if penetrated by a horizontal crack as evidenced from research by University of Colorado
- If the evaluation indicates the section has cracked all the way through (limiting case), you should consider uplift pressures no greater than those associated with tailwater at the downstream face
- (Global instability at foundation contact)

Uplift Criteria

Use existing instrumentation (uplift data, piezometers, etc.) to calibrate the analysis when applicable.

Applies to internal instability and global instability at the contact
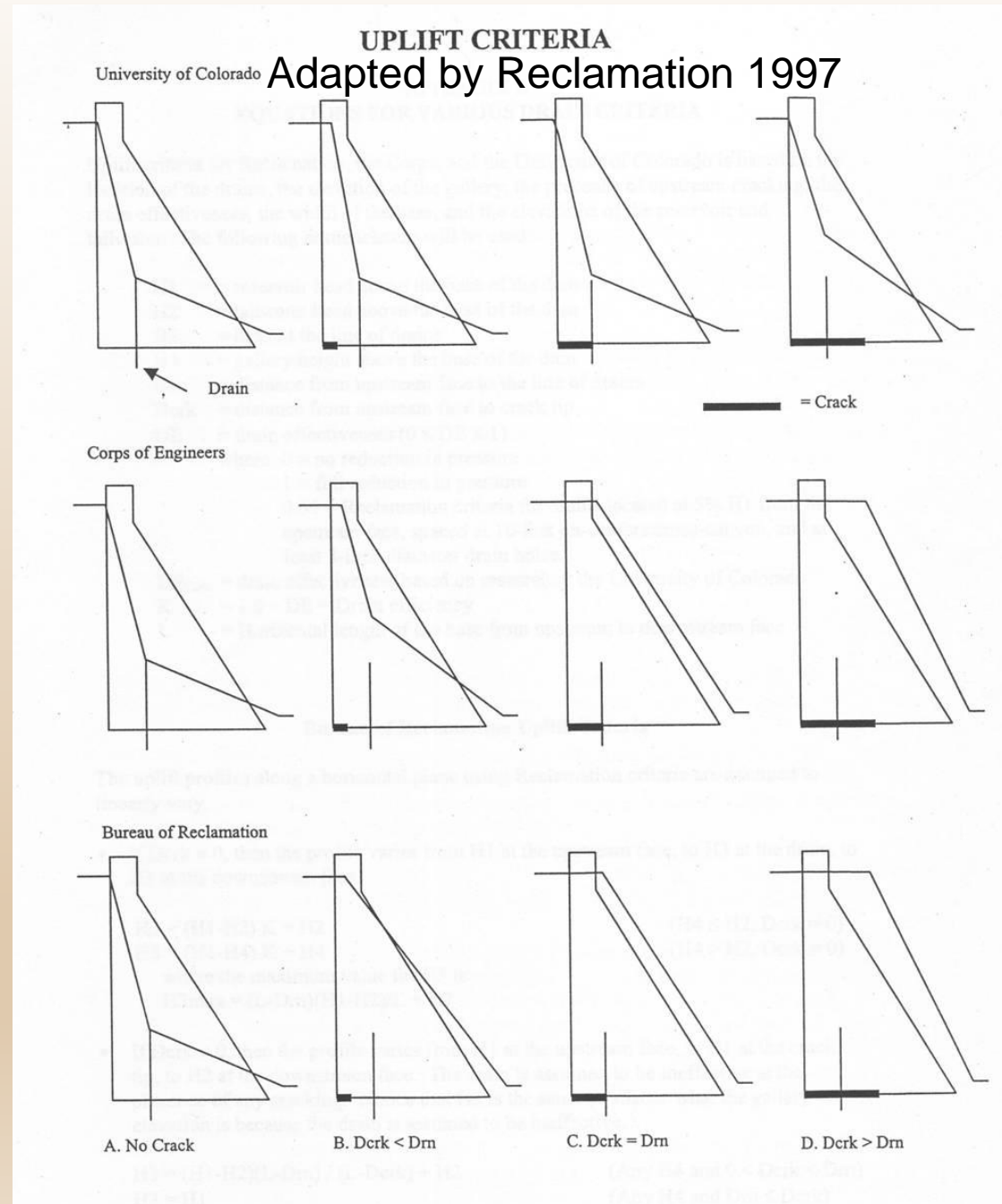
Leaking Lift Joints

- Not necessarily un-bonded

- Friant Dam – numerous leaking lifts, but core showed them to be intact (could be more porous zone or contraction joint leaks running along downstream lift line)

- Stewart Mountain Dam – few leaks but weak joints

- Check construction records to get a sense for how likely the joints are to be bonded

- Good joint treatment would include water curing tops of lifts, green-cutting (or sand blasting) laitance, richer mix/smaller aggregate on top of cured concrete, and proper vibration of the concrete during placement (see concrete properties chapter)

Event Trees

Risks Under Normal/Flood Loading Only

Event Tree

|					
	High Load Range	3.0%		Yes	4.8E-04
		0			30
			Sliding Instability		1.45045E-05
			0.014504476		30
				No	100.0%
					0
					0.029985496 0

Event tree diagram for Concrete Gravity Dam Static — Reservoir Load Range 0.000790278

- High Load Range — 3.0% — Sliding Instability 0.014504476
  - Yes 4.8E-04 / 30 → 1.45045E-05 / 30
  - No 100.0% / 0 → 0.029985496 / 0
- Load Range 4 — 5.0% — Sliding Instability 0.004774371
  - Yes 1.6E-04 / 30 → 7.95729E-06 / 30
  - No 100.0% / 0 → 0.049992043 / 0
- Load Range 3 — 11.0% — Sliding Instability
  - Yes 4.81E-05 / 30 → 5.29271E-06 / 30
  - No 100.0% / 0 → 0.109994707 / 0
- Load Range 2 — 8.0% — Sliding Instability 0.00012819
  - Yes 8.55E-06 / 15 → 6.83682E-07 / 15
  - No 100.0% / 0 → 0.079999316 / 0
- Low Load Range — 22.0% — Sliding Instability 1.43552E-06
  - Yes 2.87E-07 / 5 → 6.31631E-08 / 5
  - No 100.0% / 0 → 0.219999937 / 0
- < Threshold — 51.0% / 0 → 0.51 / 0

Load Range

Sliding Instability

<- Annualized Loss of Life

Annual Failure Prob =   2.85013E-05

- Use probabilistic limit state analysis results for 2-D analysis sections and various loads to provide basis for risk estimates
- Account for any 3-D effects judgmentally (as part of elicitation methods)
- Prudent to use tighter ranges around critical load levels (excessive heel stresses, etc)
- Use as input to event trees for risk estimate

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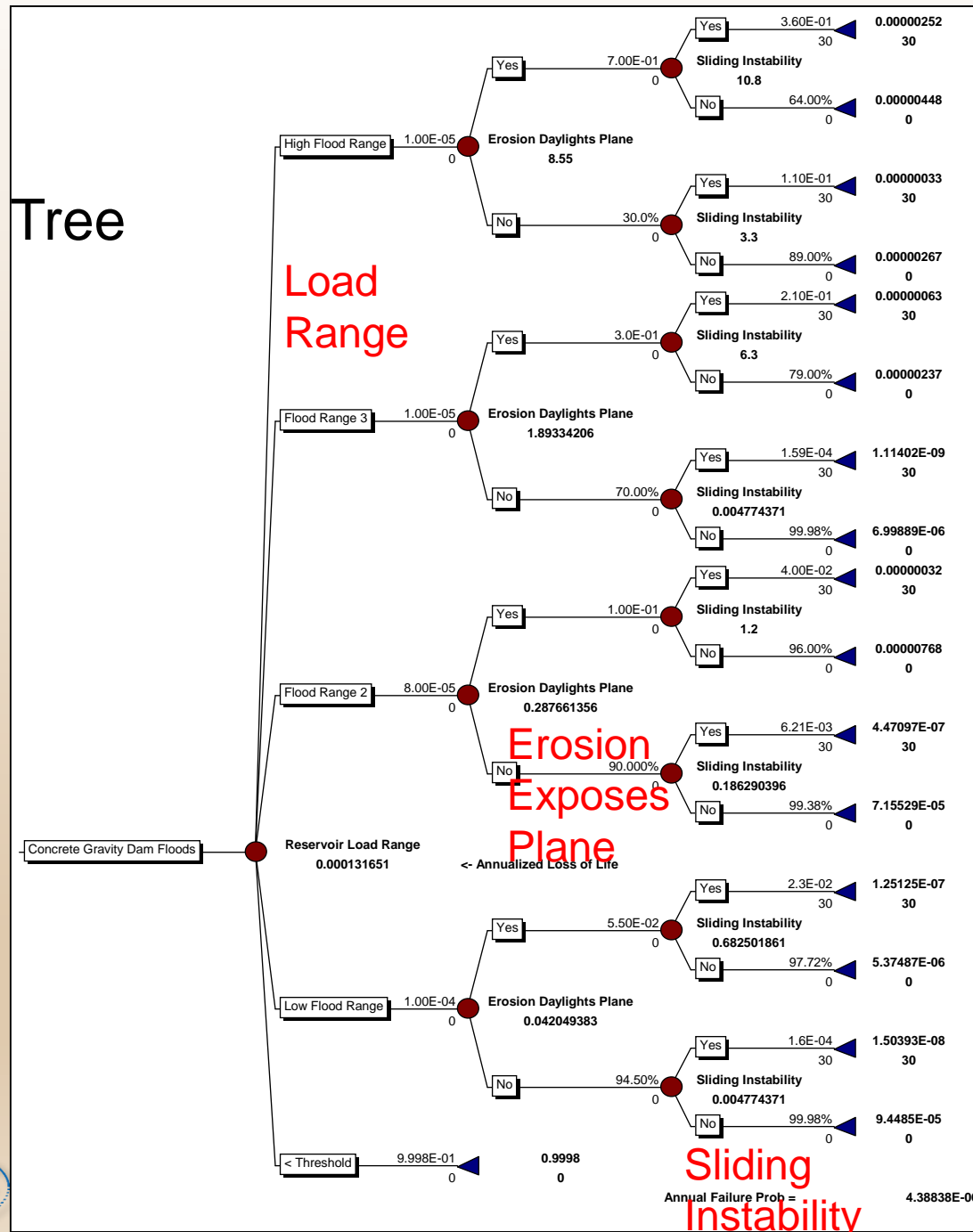
Overtopping/Spwy Releases Erode Foundation

- Careful of nappe and tailwater forces (may be smaller due to flow rates and aeration)
- Pay attention to potential erosion of rock providing passive resistance (Is there sufficient duration of spillway releases?)
- Will erosion open (daylight) a weak plane?
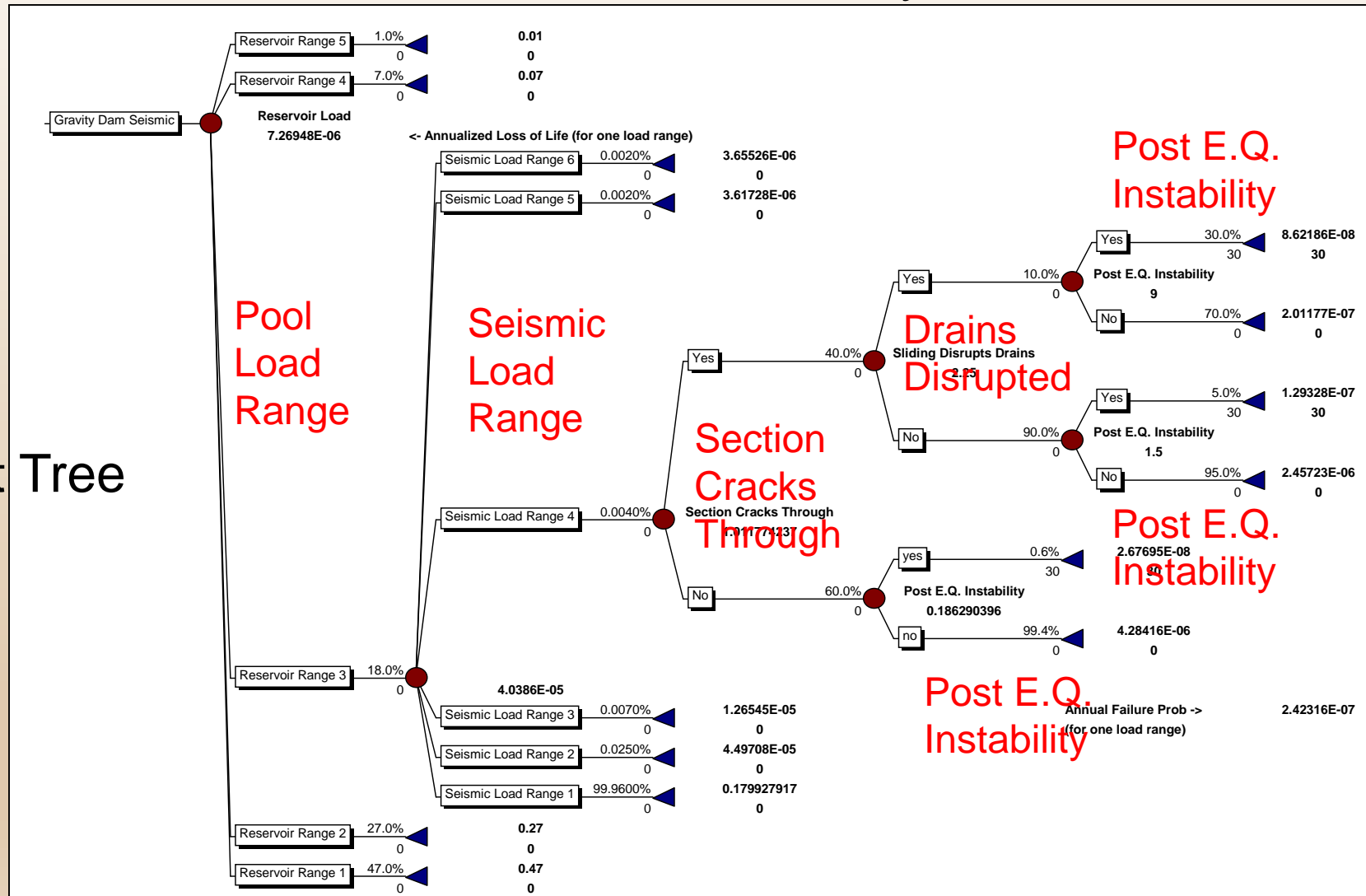- Fully develop event tree and estimate through combination of analytical and elicitation methods

Seismic Risks

Seismic Risks

Internal or foundation contact instability failure modes

Seismic Risks

Things to Consider Evaluating for EQ Loading

- Time-history finite element analysis usually required
- Amplification and damping are important considerations
- Likelihood of cracking through the section
- Likelihood of sufficient displacement to displace drains and increase uplift
- Likelihood of enough displacement to fail structure during shaking
- Likelihood of post-earthquake instability
- Dependent on earthquake load and reservoir level at time of earthquake
- Consider 3-D effects

Likelihood Section Cracks Through

- Nonlinear finite element analysis

- 2-D or 3-D

- Can also use linear elastic analysis and procedures outlined in concrete properties considerations

Important Note: Nonlinear analysis is not for the faint of heart. Make sure you thoroughly test your model. Make sure it can give the correct answer to simple problems, etc. Build the case for why someone should believe the results.


Internal instability failure mode
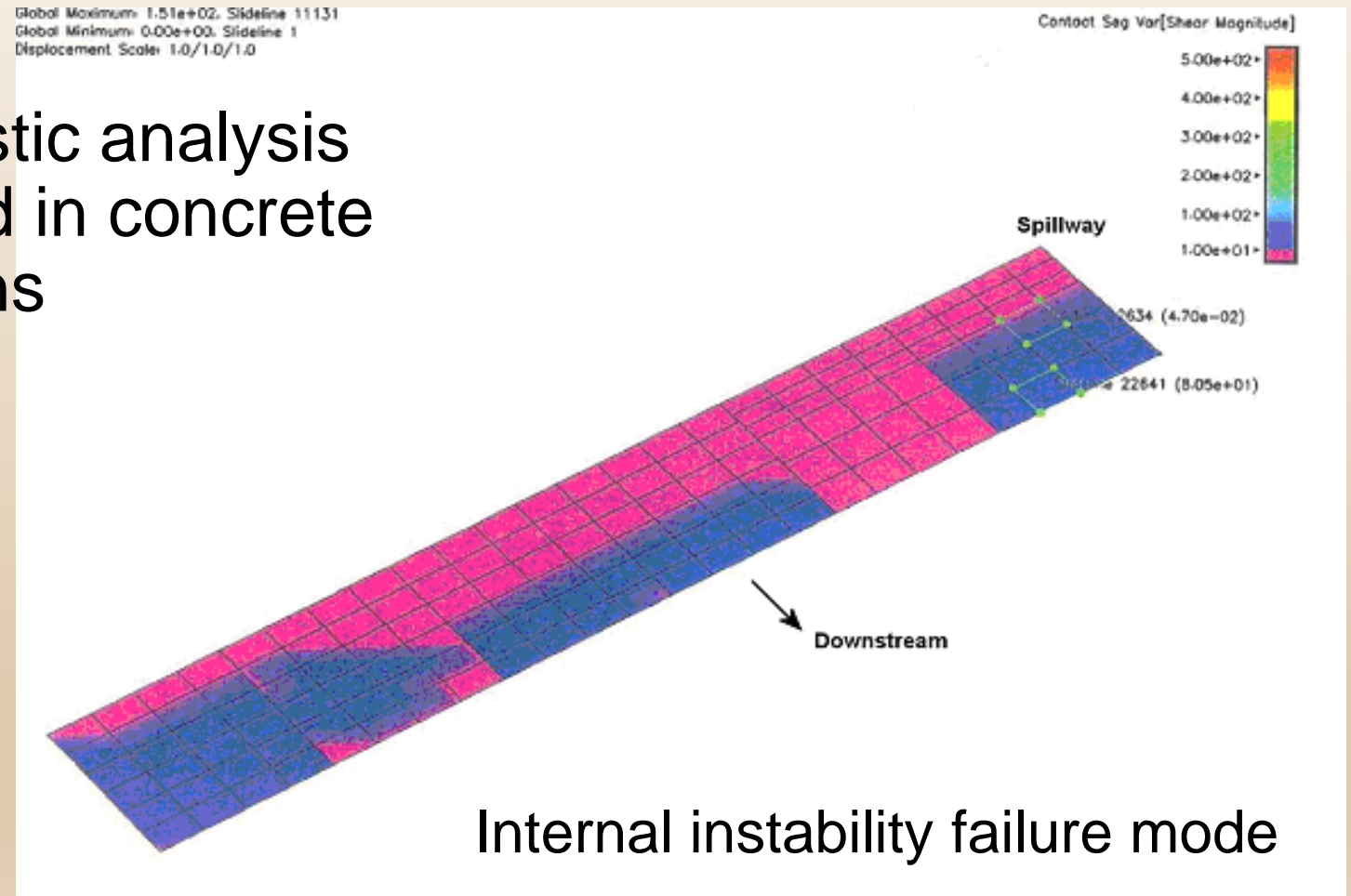
Likelihood of Cracking Through (Example)

- Adverse Factors
    - Tensile stress on u/s face exceeds estimated dynamic tensile strength for upper load ranges
    - Cracks may propagate more readily than nonlinear analysis accounts for
- Favorable Factors
    - Tensile stress on u/s face is less than estimated dynamic tensile strength for most load ranges
    - Coring showed good bond at lift joints
    - Nonlinear analysis showed only one monolith would crack through at upper load range
- Identify Key Factors and Build the Case for Estimate

Likelihood of Shearing Drains

- Nonlinear finite element analysis
- Newmark type analysis

Internal or global contact instability failure mode
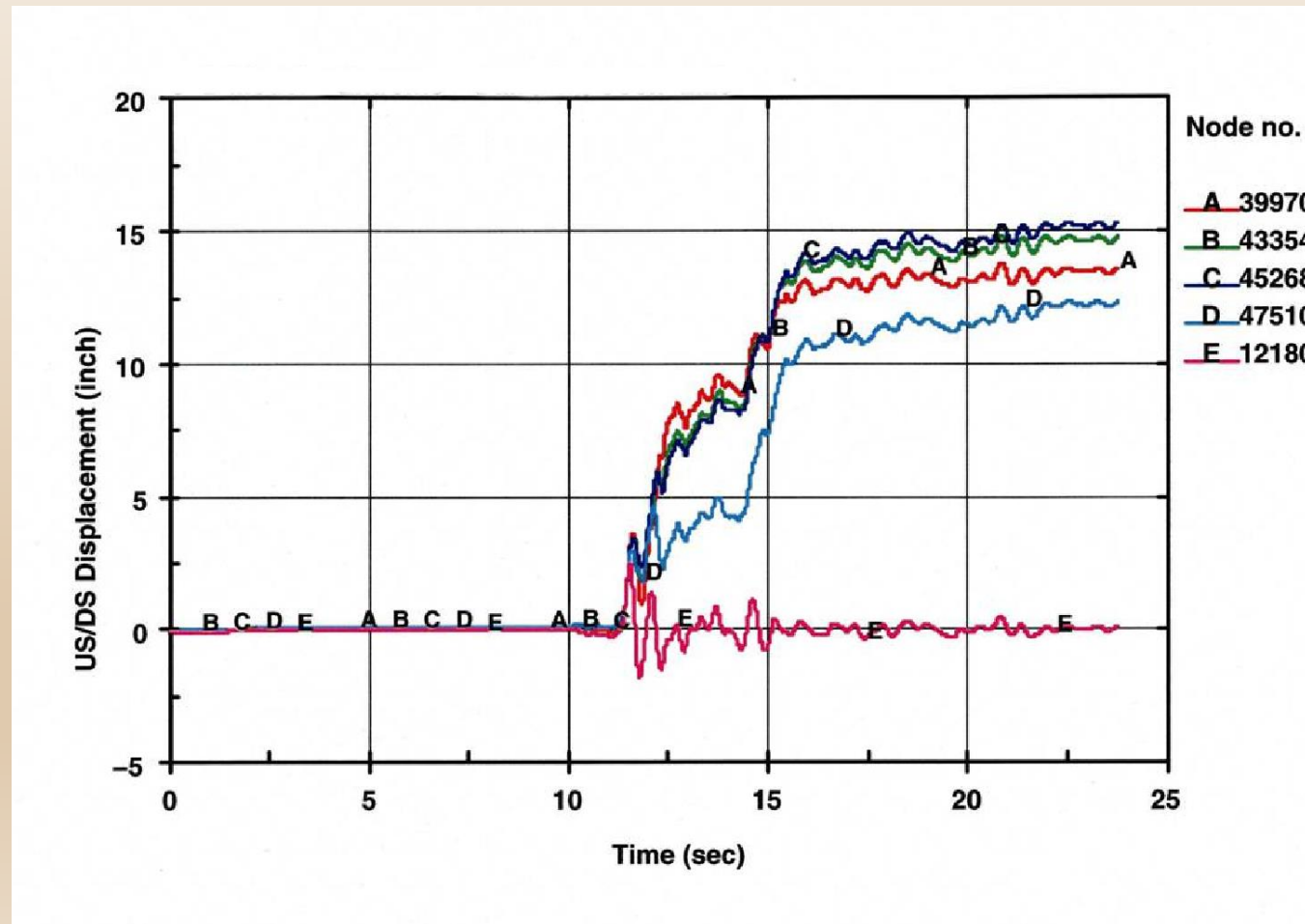
Likelihood of Displacement/ Increase in Uplift (Example)

- Adverse Factors
  - Nonlinear analysis showed displacements greater than drain diameter at upper load range.
  - Dilation on sliding plane could increase uplift without displacing drains
- Favorable Factors
  - Nonlinear analysis showed displacements less than ½ the drain diameter for most load ranges
  - Nonlinear analysis assumed lift was cracked at beginning of E.Q. when in fact it is bonded
  - Nonlinear model did not include embankment wrap-around which could reduce sliding at ends, causing rotation and binding at contraction joints
- Identify Key Factors and Build the Case for Estimate

Likelihood of Post Earthquake Instability

- Use probabilistic limit state analysis of damaged section for various scenarios
    - Partially cracked section
    - Fully cracked section but drainage intact
    - Fully cracked section with drains sheared

Takeaway Points

- Stress concentrations or weak joints are key locations for potential gravity structure instability

- Foundation contact may be strong due to very rough blasted surface

- Many evaluations rely on probabilistic limit state analysis

- Seismic risk analyses typically rely on different analyses and judgmental probabilities due to the large number of analyses required

Questions or Comments?

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Possible Exercise

- Given results from an EAGD_slide or other finite element analysis, Newmark analysis, and post-earthquake probabilistic stability analysis, estimate the likelihood of cracking through, and the likelihood of enough displacement to result in breach during the earthquake or post-earthquake.

- Note: This could be part of a larger exercise where dynamic concrete tensile strength is estimated and amplification factors are given for evaluating spillway gates and piers.